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# Enhancing Diesel Combustion Efficiency with Multi-Stage Fuel Injection: Applications in Maritime and Heavy-Duty Agricultural Engines

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## ABSTRACT

Diesel engines are extensively used worldwide, particularly in Iran, for power generation, ship propulsion, and agricultural machinery such as tractors. This study examines the performance of a heavy-duty diesel engine by evaluating four different fuel injection rate models using computational fluid dynamics. Results indicate that the triangular injection rate yields optimal performance, improving brake-specific fuel consumption by 5.5% and increasing peak combustion chamber temperature compared to other models. Reducing the nozzle diameter from 330 to 190 microns enhances combustion efficiency and lowers carbon monoxide (CO) emissions by 15%. Shortening the injection duration to 2 milliseconds improves specific fuel consumption by 3.3%, reflecting better combustion performance. Additionally, a spray angle of 147.5 degrees optimizes fuel-air mixing, leading to more complete combustion and minimal CO emissions. Finally, a 7.5% exhaust gas recirculation rate is identified as the optimal balance for reducing both soot and nitrogen oxides ($NO_x$) emissions.

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## INTRODUCTION

Diesel engines are indispensable in the agricultural sector, where they power a wide range of heavy-duty machinery such as tractors, harvesters, and irrigation systems. These engines are crucial for enhancing productivity and efficiency in farming operations. As the agricultural industry seeks more sustainable solutions, the integration of biofuels into diesel engines has gained significant attention. Biofuels, derived from renewable resources, present a promising alternative to traditional fossil fuels, offering the potential to reduce greenhouse gas emissions while maintaining engine performance. The optimization of diesel combustion, especially through fuel injection strategies, is vital for improving biofuel utilization in agricultural machinery, thus contributing to the sector's move towards cleaner and more environmentally friendly energy solutions (Carvalho et al., 2021; Krogerus et al., 2016).

Recent developments in the fuel processing technology and creation of carbon neutral combustion systems based upon hydrogen, ammonia and oxymethelyne ethers are becoming a trend for future propulsion systems research and developments. However these technologies are growing up rapidly, still have bot become successful in the vehicles industry. One main issue for the synthetic fuels to be generally used are the high amount of production costs and the unfavorable heating value. Indeed, to overcome this issues Diesel which nowadays is the main fuel being utilized in maritime, agricultural, and road transportation systems needs to be studied in order to create cleaner combustion with lower amount of unburnt carbonic emissions and higher amount of performance (Ahmadipour et al., 2019; Lovarelli & Bacenetti, 2019; Paykani et al., 2022). Spray strategies could be the main key for the diesel to enhance its operation. As Niknam et. al. investigated the spraying of Diesel-Natural gas into the combustion chamber and found this method could be effective for soot reduction up to 69% (Niknam et al., 2023). The overall trend of reducing nitrogen oxides ($NO_x$) and increasing soot levels by delaying the injection timing is consistent across various injection strategies. This phenomenon occurs because postponing the injection reduces the intensity of the premixed combustion phase, which in turn increases soot formation. Additionally, the lower flame temperature associated with delayed injection limits soot oxidation and decreases nitrogen oxide formation (Ji et al., 2022; Kaplan, 2019). Key parameters such as nozzle design, fuel injection pressure, injection start and duration, as well as the shape and rate of injection, must be optimized based on the combustion chamber geometry, the degree of swirl, and the pressure within the cylinder. Research conducted by Yan et al. indicates that optimizing swirl values and effectively regulating the injection process can lead to improvements in engine thermal efficiency of approximately 3% and 1.5%, respectively (Chen et al., 2020; Yan et al., 2017) .In an experimental study by Qi et al. on a direct injection diesel engine, it was observed that increasing the exhaust gas recirculation (EGR) rate resulted in a slight increase in specific brake fuel consumption and soot emissions, while nitrogen oxide emissions decreased significantly. At high EGR rates, the maximum pressure released was lower, and delaying the main injection timing slightly reduced specific brake fuel consumption (Qi et al., 2011). Furthermore, Deepak et al. investigated various EGR rates and found that while nitrogen oxide levels and exhaust gas temperatures decreased with EGR usage, higher carbon deposits were noted on engine components, leading to increased wear, particularly on piston rings and cylinder bushings, which is undesirable (Agarwal et al., 2011).Additionally, experiments conducted by Kim et al. on a high-speed diesel engine revealed that the penetration of the injected fuel from an injector with a narrower injection angle was greater than that from an injector with a wider angle. This well-established relationship suggests that injectors with narrow angles may be particularly effective in diesel engines with deeper piston bowls, as they facilitate improved swirl and more effective fuel-air mixing (Kim et al., 2016). Kharkeshi et al. conducted numerical simulations to study the effects of varying fuel injection duration from 14.6 to 35.6 degrees. Their results stated that the single-spray fuel jet injection duration setting directly affects the probability of uncontrolled knock occurrence. Moreover, emissions data showed that while $CO_2$ and $NO_x$ levels increased, carbon monoxide emissions decreased with shorter injection times (Kharkeshi et al., 2021). Modern control systems are equipped with sophisticated algorithms that adjust injection characteristics based on varying operating conditions. This capability allows for the implementation of advanced spray technologies, such as piezoelectric injectors, which offer faster response times and more precise fuel delivery. The ability to dynamically adapt injection strategies enhances engine performance, particularly under variable load and speed conditions, resulting in improved fuel efficiency and reduced emissions (Cowart et al., 2015; Zhou et al., 2021).

In this study, an optimal injection rate was selected from four different spray patterns to determine the best performance of the engine. A comprehensive analysis of the combustion process and the factors influencing the spray in a diesel engine was then conducted. Specifically, four fundamental parameters affecting the quality and manner of the injection and mixing quality were examined: duration, timing, nozzle diameter, and spray angle. Additionally, the combustion parameters, including thermodynamic variables and the distribution of species mass fractions, were analyzed. A multi-stage spray with a simulated triangular injection rate was also investigated, and the results will be discussed further in this report.

## MATERIAL AND METHODS

To achieve an accurate simulation with minimal error, it is essential to first understand the physics of the problem and the governing equations involved. This understanding allows for the correct selection of solution methods and the implementation of precise modeling to effectively tackle the problem at hand. In this chapter, the governing equations of the flow will be discussed and analyzed from a theoretical perspective, and finally, the approach to modeling will also be presented.

The conservation of mass equation, commonly referred to as the continuity equation, asserts that the mass entering and exiting a control volume remains constant. This principle can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

In this equation, the term $\partial\rho/\partial t$ represents changes in fluid density with time, since compression is also a part of the combustion process, fluid density must be modeled as a variable with time. Also, the term $\nabla\cdot(\rho v)$ also expresses the divergence of the flow velocity vector within the computational domain.

In addition to the above equation, the momentum conservation equation also relates the rates of change of momentum in a control volume to the net forces acting on the system. In the case of an Internal combustion engine, this equation represents the complex interactions between the combustion process, fluid dynamics, and mechanical components, as follows:

$$\rho\left(\frac{\partial u}{\partial t} + u.\nabla u\right) = -\nabla p + \nabla.\tau + \rho g \tag{2}$$

If the flow is turbulent, the momentum equation must be modified. In this case, turbulence is modeled using approaches based on the concept of eddy viscosity, which involves introducing an additional term into the momentum equation to account for the effects of turbulent viscosity.

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x} - \left(\frac{\partial \overline{\acute{u}^2}}{\partial x} + \frac{\partial \overline{\acute{u}\acute{v}}}{\partial y} + \frac{\partial \overline{\acute{u}\acute{w}}}{\partial z}\right) + \vartheta \nabla^2 u \tag{3}$$

It can be seen that in the momentum equation, the terms of disturbance stresses which themselves form a tensor are added.

$$R_{ij} = -\rho(\overline{\acute{u}_i \acute{u}_j}) = -\rho \begin{bmatrix} \overline{\acute{u}^2} & \overline{\acute{u}\acute{v}} & \overline{\acute{u}\acute{w}} \\ \overline{\acute{v}\acute{u}} & \overline{\acute{v}^2} & \overline{\acute{v}\acute{w}} \\ \overline{\acute{w}\acute{u}} & \overline{\acute{w}\acute{v}} & \overline{\acute{w}^2} \end{bmatrix} \quad (4)$$

In this research, the Bouznesque equation was employed to calculate the amount of eddy viscosity using the k-zeta-f model. Hence, by incorporating the turbulence stress term into the momentum equation, the equation of motion can be solved for the fluid. The mathematical description of the eddy viscosity based approach turbulency model is provided below:

$$-\rho\overline{\acute{u}_i \acute{u}_j} = 2\mu_t S_{ij} - \frac{2}{3}\rho k \delta_{ij} \quad (5)$$

To accurately describe the chemical reactions occurring in the combustion chamber and to control the reaction kinetics, the species transfer equation must be employed. This equation accounts for the precise quantities of all species involved and characterizes the mixing, penetration, and evaporation of the two fluid phases. The general form of the species transfer equation is mathematically expressed as follows.

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{v} Y_i) = -\nabla \vec{J_i} + R_i + S_i \quad (6)$$

The influencing factors in the species transport equation include $Y_i$ ، $J_i$ ، $R_i$ and $S_i$ parameters. $Y_i$ is the introduced species, $J_i$ determines the penetration of the species, $R_i$ Is the species production rate after the reaction and $S_i$ , which is the source term of the above equation, enters the new equation as a parameter of the species created in the previous reaction. It should be noted that the relationship between the species transport equation and the turbulence equation is established through the penetration parameter$J_i$. In this equation $R_i$ is calculated by the combustion equation or reaction mechanisms, but$J_i$, which is the penetration parameter in turbulent flow, is calculated by the momentum equation.

**Table 1.** Numerical model used

| Physics | Specified model |
|---|---|
| Combustion | ECFM 3z |
| Differencing scheme | Simple |
| NOx Emission | zeldovich |
| Spray | DPM |
| Evaporation | Dukowich |
| Turbulancy | k-zeta-f |

In order to determine the desired outputs related to the emission and performance of the case being studied, appropriate solution methods and simulation tools must be chosen. In this research, the diesel engine used for model validation is the single-cylinder version of Caterpillar 3401 heavy-duty engine that its specifications are given in Table (2).

**Table 2.** Refrence Caterpillar 3401 diesel engine specifications

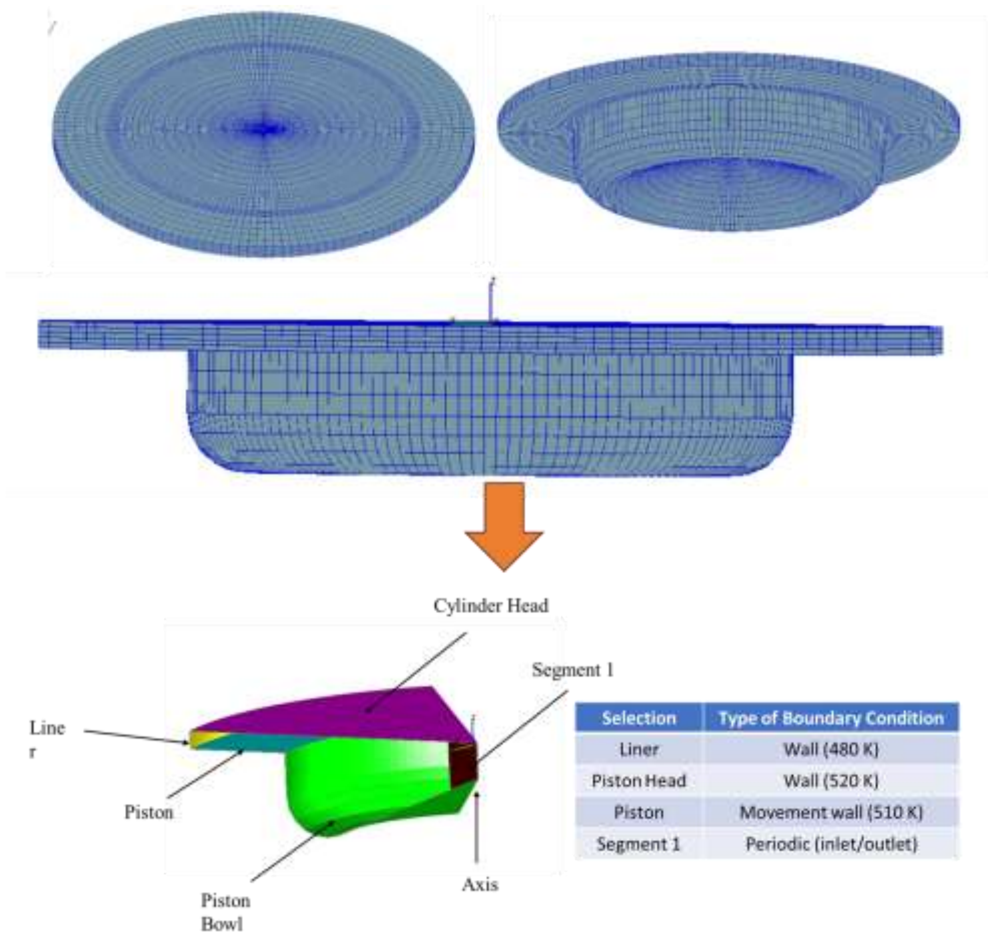
| Engine type | Caterpillar 3401 |
|---|---|
| Bore × stroke | 13.719cm × 16.51cm |
| Compression ratio | 15.1:1 |
| Displacement | 2.44 |
| Connecting rod length | 26.162 cm |
| Squish clearance | 4.14 mm |
| IVC/EVO | -147 ATDC/134 ATDC |
| Engine speed | 1600 rpm |

Also, characteristics of the single-cylinder engine's injection system studied in this research, has been mentioned in Table (3):

**Table 3.** Characteristics of injection system

| Injection system | Common rail |
|---|---|
| Injection pressure | 120 MPa |
| Number of hole | 6 |
| SOI(Start of Injection) | 10 BTDC |
| Injection duration | 21.5 CA |
| Fuel mass per cycle | 2.7e-5 kg |

Considering the axially symmetrical nature of the fuel injection process in the studied engine, and since the number of nozzle holes are is 6, only one-sixth of the sector could be modeled by assuming axial symmetry and check the results. Figure 1 shows the boundary conditions used in this sector are also depilated in test below.




| Selection | Type of Boundary Condition |
|---|---|
| Liner | Wall (480 K) |
| Piston Head | Wall (520 K) |
| Piston | Movement wall (510 K) |
| Segment 1 | Periodic (inlet/outlet) |

**Figure 1**. The examined sector and the bouundary condition of the computational domain

## RESULTS AND DISCUSSION

As illustrated in the figure below, the numerical results derived from the laboratory findings of Mobasheri et al. demonstrate an acceptable level of accuracy when compared to the experimental results (Mobasheri et al., 2011). Specifically, an average of the obtained results revealed that the modeling outcomes differed by approximately 4% in the in-cylinder pressure peaks, indicating a satisfactory degree of accuracy in the modeling process.

As illustrated in Figures2, decrease in grid size leads to a reduction in the distance between the simulated maximum pressure and the experimental sample, resulting in significantly closer outcomes. To achieve optimal accuracy, a grid size of 2 mm was selected for the continuation of simulations and for conducting more extensive studies on spraying. As previously mentioned and illustrated in Figure 3, the combustion conditions examined in the studied diesel engine exhibit axial symmetry. Consequently, rather than modeling the entire piston bowl, it is sufficient to model only a section of it.

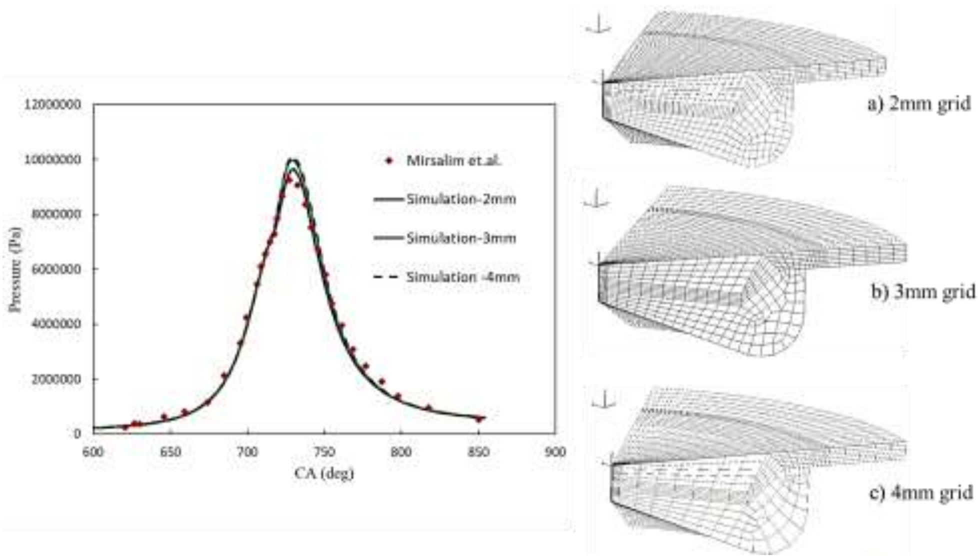



**Figure 2**. Validation and Grid independency of the numerical results

Considering the operating conditions of the initial engine, four different spray rate profiles have been defined for the baseline engine over a duration of 2.5 milliseconds. We will then analyze the results of the obtained parameters and identify the optimal configuration for subsequent analyses.In the figure below, the four spray rate profiles are presented, showing the fuel injection amount for the baseline engine vesus the injection duration.

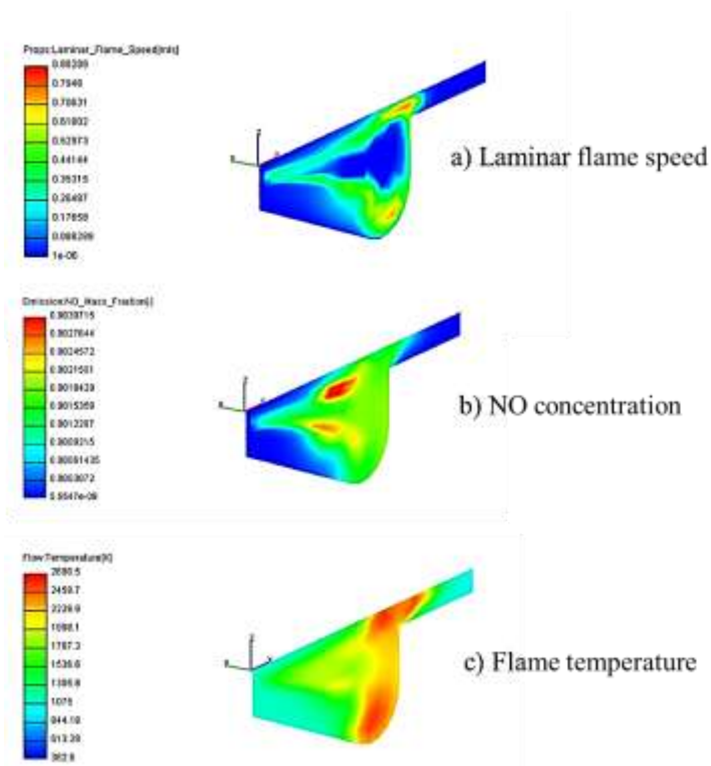



**Figure 3.** Local distribution of flame speed, temperature and Nitrogen Oxids in the combustion chamber.

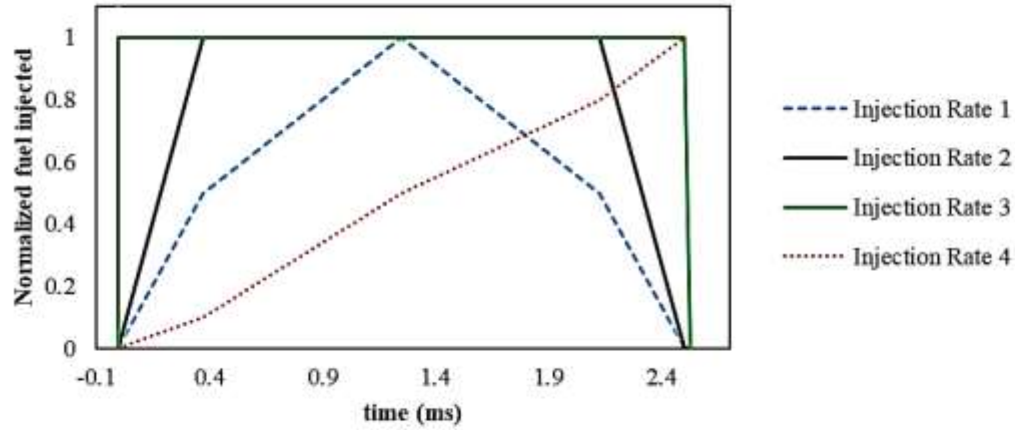
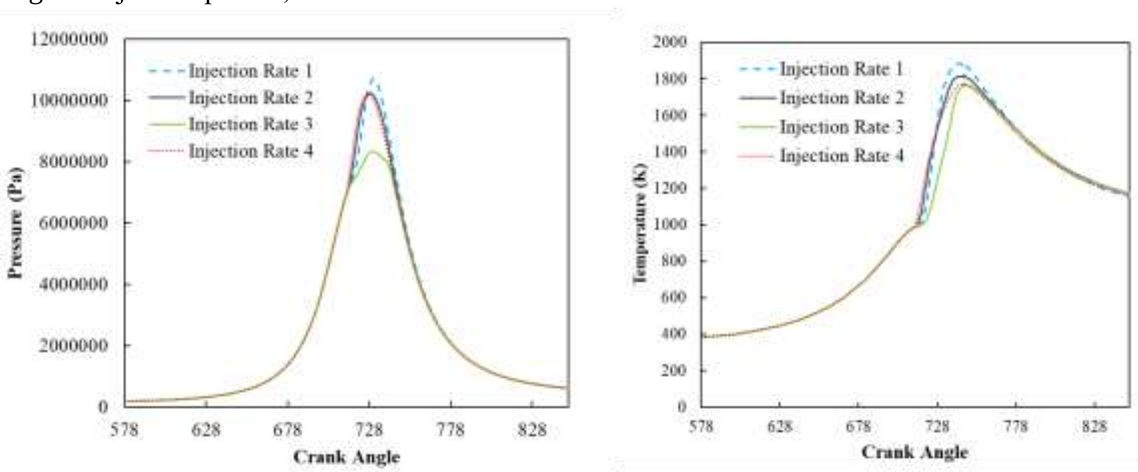



**Figure 4.** Various investigated rates of injection

The findings indicate that the fuel injection rate significantly impacts pressure distribution within the combustion chamber. Specifically, an improper injection rate (rate no. 4) leads to delayed combustion, resulting in a minimal pressure increase and a lower maximum pressure compared to injection rates 1 and 3. Conversely, a triangular injection profile, with a constant start of injection at 10 BTDC, achieves a steeper pressure increase and higher average peak temperature, reaching nearly 1900 K°.This increased temperature is attributed to more complete combustion, suggesting that the triangular profile promotes better mixing and higher thermal efficiency.




| | Engine Specific output | Inj-rate1 | Inj-rate2 | Inj-rate3 | Inj-rate4 |
|---|---|---|---|---|---|
| 1 | Air Fuel ratio (-) | 24.91 | 24.91 | 24.91 | 24.91 |
| 2 | Brake mean effective pressure (bar) | 12.03 | 11.66 | 11.28 | 10.91 |
| 3 | Brake specific fuel consumption (kg/kWh) | 0.1988 | 0.2051 | 0.2119 | 0.2192 |
| 4 | Thermal efficiency (-) | 0.44 | 0.43 | 0.41 | 0.40 |
| 5 | Power (kW) | 40.12 | 38.92 | 37.69 | 36.47 |
| 6 | Torque ( N.m) | 239.44 | 232.26 | 224.96 | 217.65 |

**Figure 5.** Effects of injection rate variation on the performance and pressure/temperayure variation in the combustiuon chamber

Reducing the nozzle diameter to 190 micrometers significantly increases the average pressure inside the cylinder, achieving maximum pressure values up to 10 bar compared to the initial engine. Furthermore, decreasing the injection duration from 4 ms to 2 ms markedly enhances both the rate of pressure rise and peak pressure, indicating a more rapid and intense combustion process. Although, in theory, this leads to more complete combustion and lower pollutant production, excessive pressure increases molecular vortex motion, resulting in higher fluid pressure exerted on the piston bowl. Therefore, it is crucial to monitor additional parameters, such as knocking and ignition timing, to prevent potential engine damage. Furthermore, employing a stratified injection profile could lead to a 71% increase in peak pressure, which enhances performance. However, a sharp pressure gradient may not be favorable, as it could negatively affect engine durability.

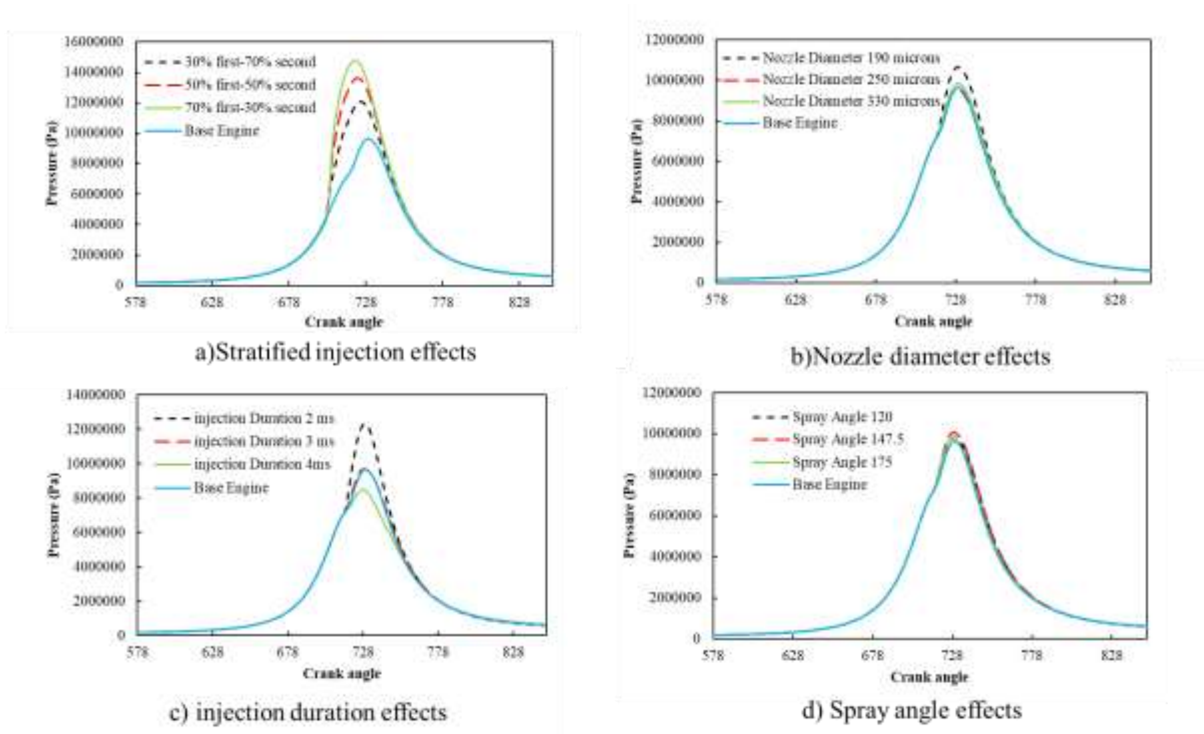



**Figure 6.** Pressure variations with different spraying strategies

The findings highlight the significant impact of injection strategies on the heat release rate (HRR) and emissions in diesel engines. As illustrated in figure 7, while increasing the percentages of the fuel being injected into the chamber, a faser combustion occurs due to reaching the fuel mixture to its auto ignition limit. This causes sharp and early increase in the rate of heat release. Also, investigating spray angle, duration, and particle diameters shows that considering a thin injector tip in association with 147.5 degree of spraying jet, and 2 ms of the duration could increase the speed of combustion and consequence in higher rates of heat release.

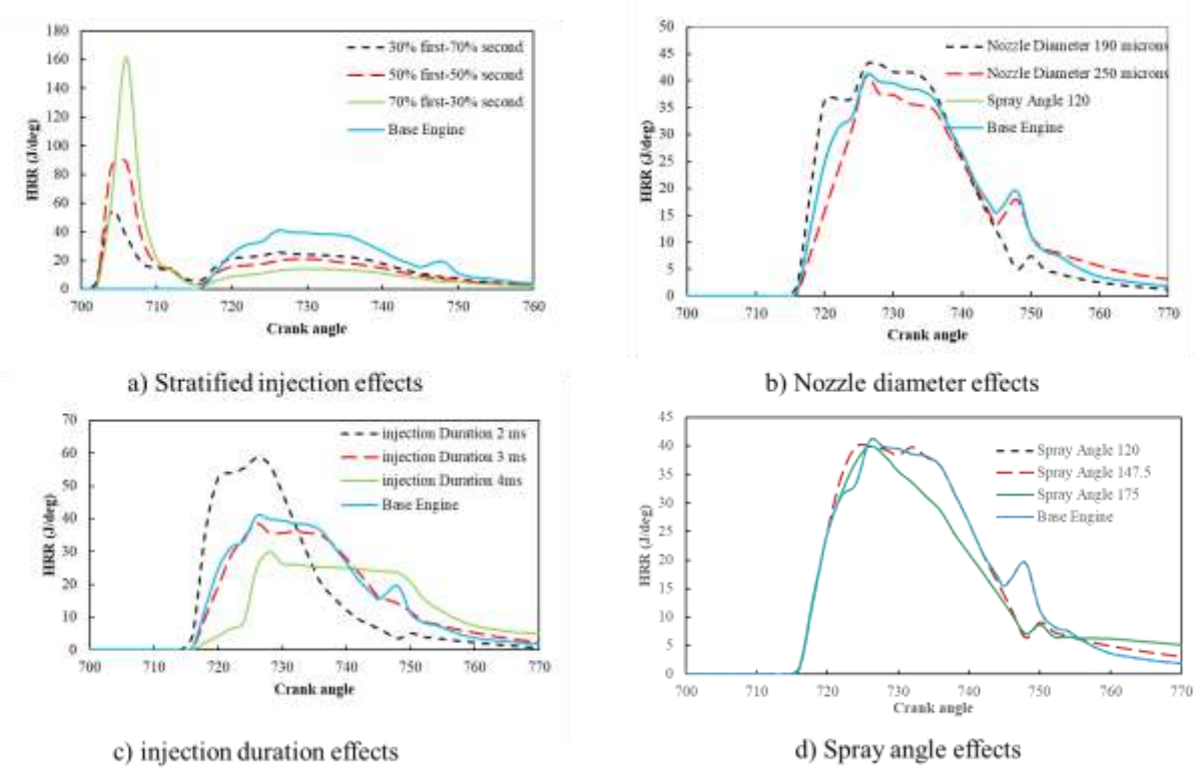



**Figure 7.** Rate of heat release variations with different spraying strategies

The findings reveal a strong correlation between thermal nitrogen oxides ($NO_x$) and carbon dioxide emissions, indicating that increased fuel injection in the initial stage leads to higher $NO_x$ production due to elevated combustion temperatures and enhanced chemical reactions. Specifically, using a narrower injection nozzle results in a maximum heat release rate that is 2 J/degree higher than other conditions, accelerating the decomposition of nitrogen ($N_2$) and oxygen ($O_2$) into reactive radicals, thereby increasing $NO_x$ emissions. Optimizing the injection angle is also critical for maximizing energy extraction from fuel combustion. Adjusting the injection angle to 147.5 degrees can reduce heat loss to the cylinder wall from 31.4 kW to 29.1 kW, minimizing thermal inefficiencies and improving fuel penetration. Since heat is a primary contributor to $NO_x$ pollution, controlling combustion chamber temperature is essential for emission reduction. Notably, an injection duration of 2 milliseconds results in significantly higher heat release and $NO_x$ production compared to longer durations. To address these emissions, strategies such as selective catalytic reduction (SCR), water injection, and exhaust gas recirculation can be implemented. These findings emphasize the importance of optimizing injection parameters and combustion conditions to enhance engine performance while minimizing emissions.

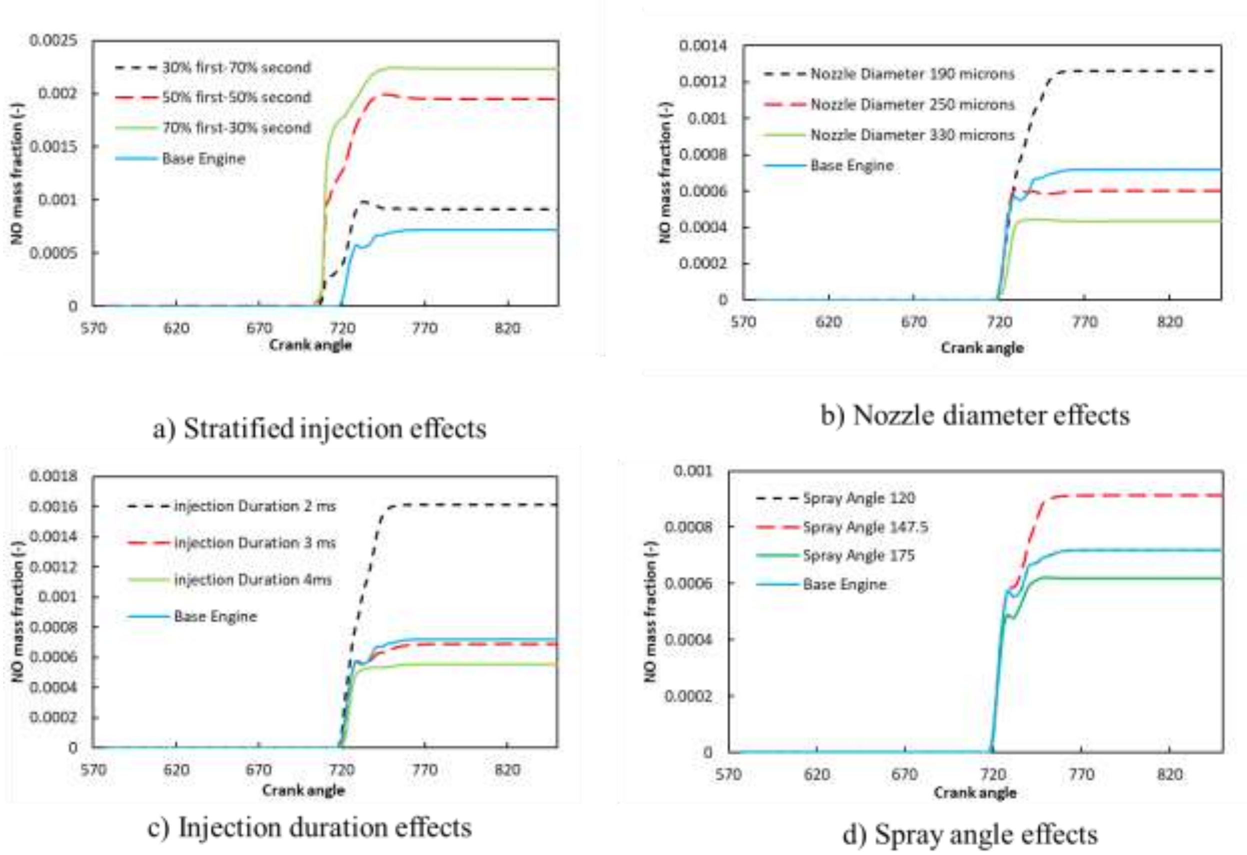



**Figure 8.** Instantaneous $NO_x$ emission with different spraying strategies

The findings also highlight the importance of both the timing of ignition and the reduction of harmful emissions in diesel combustion. A slight ignition delay in diesel auto-ignition can lead to suboptimal ignition timing. Reducing carbon monoxide (CO) emissions not only improves combustion efficiency but also protects human health, while carbon dioxide ($CO_2$) primarily contributes to the greenhouse effect. Addressing both CO and $CO_2$ emissions is crucial in the context of climate change.Numerical studies indicate that the spray angle significantly affects CO emissions. Specifically, directing the fuel towards the cylinder wall and minimizing its penetration increases CO emissions and leads to incomplete combustion. The mass fraction of CO reaches its minimum at an injection angle of 147.5 degrees, which may results in a slight increase in $CO_2$ emissions.

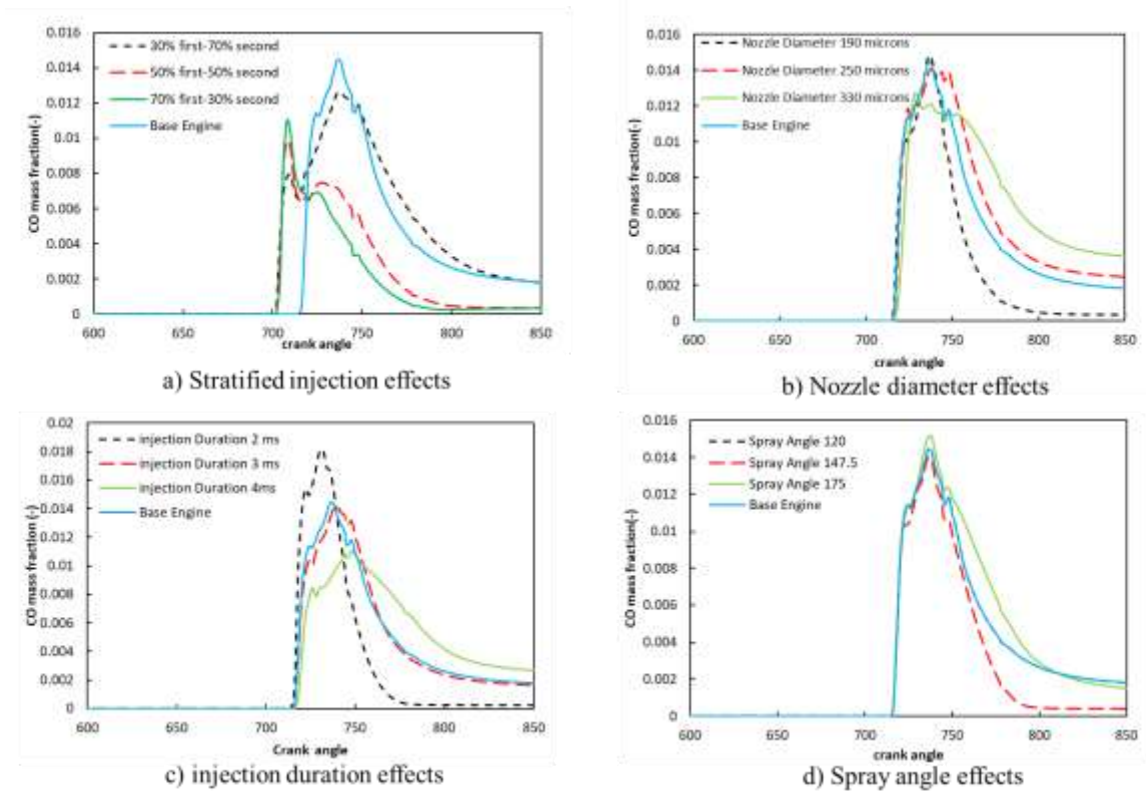



**Figure 9.** CO pollution at each crank angle with different spraying strategies

## CONCLUSIONS

In addition to examining the effects of four different fuel injection rates on diesel engine performance, this research quantitatively analyzes the injection area within the engine to determine the optimal injection angle, nozzle diameter, and fuel injection duration. For this study, the Caterpillar 3401 diesel engine commonly utilized in heavy-duty agricultural tractors or some large marine engines was considered. The results indicate the superiority of the triangular injection rate (Rate No. 1) compared to the other rates. Based on the obtained data, the following findings can be highlighted:

- The energy efficiency of the system increased by 12% with the triangular injection rate Specific fuel consumption decreased when utilizing this injection rate, indicating more optimal combustion and higher engine efficiency in this mode.
- The average temperature of the combustion chamber reached 1900 K° with the triangular spray rate, representing an increase of approximately 5% compared to other simulated cases. This suggests a more complete combustion event when this spray rate is employed.
- The use of the triangular rate resulted in increased emissions of nitrogen oxides and carbon dioxide due to more complete combustion. However, the amount of carbon monoxide emissions was also reduced.
- Furthermore, the use of a spray nozzle with a diameter of 190 micrometers led to a 13% increase in nitrogen oxide emissions while simultaneously improving carbon monoxide pollutants and overall engine performance. This improvement can be

attributed to enhanced atomization quality and better mixing of fuel with air.

• The use of injectors with shorter injection durations and higher pressures has been shown to increase the heat release rate by up to 60 J/°C. This improvement is attributed to better fuel-air mixing, achieved through finer fuel atomization, and the development of more pronounced pressure gradients in the combustion chamber. Diesel combustion consists of two phases: the premixed phase, followed by the diffusion phase. By reducing the injection duration, fuel-air mixing during the premixed phase becomes more efficient. However, if the injection time is extended while maintaining the same start of injection, the piston will eventually pass TDC, which increases the chamber volume and can result in a misfire.

• By adjusting the injection angle to 147.5 degrees, we observed a reduction of over 80% in carbon monoxide pollution compared to the original engine configuration, effectively improving the fuel-air mixture.

• Additionally, the adoption of multi-stage injection in the engine can lead to reduced pollutant emissions and higher maximum pressure and temperature. However, this approach may also increase the potential for untimely self-ignition and excessive knocking within the engine, as highlighted in previous research that warns of the limitations of the pressure rise rate. The results of this study show a significant increase in this rate, but a more detailed calculation and further investigation are needed to fully assess the implications of these findings.

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